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# **Potable water supply feasibility study for Summit Station, Greenland**



*for,*  
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## Executive Summary

This study reviews potable water production methods used in Polar Regions that may be applicable for use at Summit Station, Greenland. The two predominate methods currently in use are melting surface snow and melting subsurface ice to form a well and then extracting the melt water to the surface (a Rodriguez well or Rodwell).

There is limited published data on the energy usage for melting surface snow. For this analysis we rely mainly on the data from the existing Summit Station. The basic energy requirement to melt the snow is about 2,300 BTU/gal. This does not include the energy associated with harvesting the snow or transporting the water after it is melted, which is found to be negligible. However this is also a labor-intensive activity requiring use of personnel and heavy equipment. There are opportunities to reduce the labor in this process with a new design of the system (e.g. piping water from the melt tank to the service locations).

The feasibility of using a Rodwell at Summit was also analyzed. In this case, a subsurface well would be established in the glacial ice and melt water from the well would be pumped to the surface for treatment and distribution to point-of-use locations. The approximate sustained energy requirement for this system would be 30 - 40,000 BTU/hr, with an initial requirement of 142,000 BTU/hr for bulb start-up. These energy requirements are well within the available waste heat quantities at the current Summit Station. This feasibility study shows that a Rodwell can provide at least 10 years of service before it will need to be re-located. The specific energy requirement for this system ranges from 4,100 – 7,000 BTU/gal or 1.8 to 3.0 times higher than the current system of melting surface snow. This study shows that the lower the population is at Summit, the higher the specific energy requirement is for producing water with a Rodwell. In other words, the Rodwell is more energy efficient when it is designed to supply more water. Additional considerations, including manpower to create and maintain the Rodwell, ancillary equipment needed for operation, potential subsurface obstructions and contingency planning are also briefly discussed.

## 1. Introduction

Summit Station is a year round science support facility located on the Greenland ice sheet at an elevation of approximately 10,500 feet. Weather can range from mild in the summer at 32° F (0°C) with light winds to lower than -100°F (-73°C) with strong windstorms in the winter. Currently the population at the station varies widely from winter to summer, going from ~ 4 station personnel up to 50 support staff and scientists, respectively. On average, based on data from January of 2006 – August of 2009, this population uses 15-18 gallons of water/person/day.

There are a variety of buildings at Summit Station. The primary facility, the “Big House” contains a kitchen, dining hall, a communications office and has a bathroom and laundry facility. Other major facilities include the Greenhouse (laboratory space, bathrooms, lounge, etc.) and the Berthing Module (the main living quarters). There are a variety of other small buildings around station.

Presently, to create potable water at Summit Station, snow is harvested from a designated area on station then driven to the dump location in the shop some 600-800 feet away. The snow is dumped down a chute into the building and through a trap door into a tank where waste heat is used to melt the snow before it is piped to treatment (filter and UV). Water is piped to the Green House and is also pumped into a tank on a sled to transport it to a storage tank in the Big House. This system requires extensive manual labor. It is hoped that with the new station, dubbed Model 5, which is currently in design stages, a less labor-intensive means of potable water production will be implemented.



**Figure 1.1** Caterpillar 933 used for snow mining at Summit Station dumping snow into the chute leading to the melt tank.

Just as important as being more efficient for station personnel, it is hoped that this new design will also be more energy efficient. There are a variety of energy efficiency

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measures currently being considered to enhance the station before the Model 5 design is complete and extending the waste heat system to the Big House is a main one (Armstrong, 2010).

The objectives of this present study are two-fold. The first is to review the current approaches for providing potable water in Polar Regions. The second is to do an initial assessment of feasibility of these methods for the Model 5 design, including an assessment of a Rodriguez well to serve the potable water needs at Summit.

## 2. Review of existing methods

A literature survey was done to assess the current state of knowledge for potable water production in Polar Regions. Though over 60 references were found, many did not provide sufficient detail about actual potable water production. Of the remaining methods found many, such as desalination or reservoir systems, are not feasible at Summit Station. This left approximately 18 relevant references. These are listed in Appendix A.

Twenty-three different station systems were discussed in these references. A listing of data relating to station name, years active, type of system, station population, water production, treatment, transport system to production, transport system once potable and then any other pertinent information was compiled and is given in Appendix A; unfortunately, for some stations the data is sparse. A summary of this data is provided here. The stations reviewed were active from 1952 to present day. The most common type of potable water production is snow melting, primarily using waste heat; this has been used since the 1950s. It has been used at stations with as few as 8 people and at others with more than 100. As is currently done at Summit Station, these snow melters are most often fed by manual labor, i.e. shovels and dozers. In other cases, the systems have been augmented by strategic placement of the melting tank (as in Halley VI or Princess Elisabeth Station), snow drift collection (Neumayer Station III) or mechanical dragline (DYE 2 and 3).

Another well known technique for potable water production is using a Rodriguez well (Schmitt & Rodriguez 1960) or “Rodwell.” This was first done at Camp Century in the late 1950s and most recently at the US Antarctic Program’s Amundsen-Scott South Pole station and if feasible, is generally preferred over snow melting since it provides higher-quality water. This system requires deep glacial coverage for formation of the subsurface water bulb and a continuous energy input to maintain the bulb. This technology will be discussed as an option for Summit Station in more detail in section 3. Many recent efforts in potable water production have also focused on water recycling systems. In particular, the Belgian Antarctic station Princess Elisabeth relies on this heavily where 75% of water is used a second time, though all recycled water is used for non-potable applications.

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## 3. System analysis

We will consider two scenarios for analysis. The first will be the current water demand based on the current population at Summit. The second will be the projected water demand based on the anticipated population that the Model 5 design is intended to support.

The baseline data for scenario 1 is determined as follows. The water demand and population at Summit over the recent past (Jan 2006 – Aug 2009) is summarized in Figure 3.1. This data shows that during the winter the population is typically 4, with peak of 8-11 persons. The summer population varies between about 20 – 50 persons. The water demand reflects these trends with peak winter demand at about 1400 gal/wk, and peak summer demand at about 3400 gal/wk. Based on the data presented in Figure 3.1 it appears the summer “season” lasts from about 1 May to 30 Sept (153 days) and the winter season then goes from 1 Oct to 30 Apr and lasts 212 days. The average annual water consumption for the three full years of recorded data is 62,124 gallons with a peak of 68,236.

Scenario 2 is based on the anticipated population at Summit under Model 5 operation, which is 6 people year round except for 2 weeks during each of the months of April, August, November and February during which the population is 12. The current water consumption at Summit is 15-18 gallons of water per person per day (this may be reduced under the Model 5 design, but for the present time it is the best available estimate). From a water usage standpoint this creates a yearly demand of 45,468 gallons (based on the conservative number of 18 gallons per person per day). This is about 75% of the current amount of water used annually.

The available heat to provide this water supply currently comes from station waste heat produced by on-site generators. The amount of waste heat available is given as follows (data provided by Jeff Sever, CH2M Hill, via email 15 May 2010). The current snow melter system uses up to 60,000 BTU/hr (60 MBH) of waste heat over a 48 hr period to melt enough snow into water to supply 6 people for two weeks. As much as 142 MBH can be made available if the medium sized generator is brought on line. The glycol temperature for the waste heat recovery system ranges from 150-190 F.

### 3.1 Requirements

Scenario 1: Based on the above information for scenario 1 the following requirements for a water system are:

- Summer duration: 153 days (1 May – 30 Sept)

- Summer water demand\*: 3000 gal/wk

- Winter duration: 212 days

- Winter water demand\*: 700 gal/wk

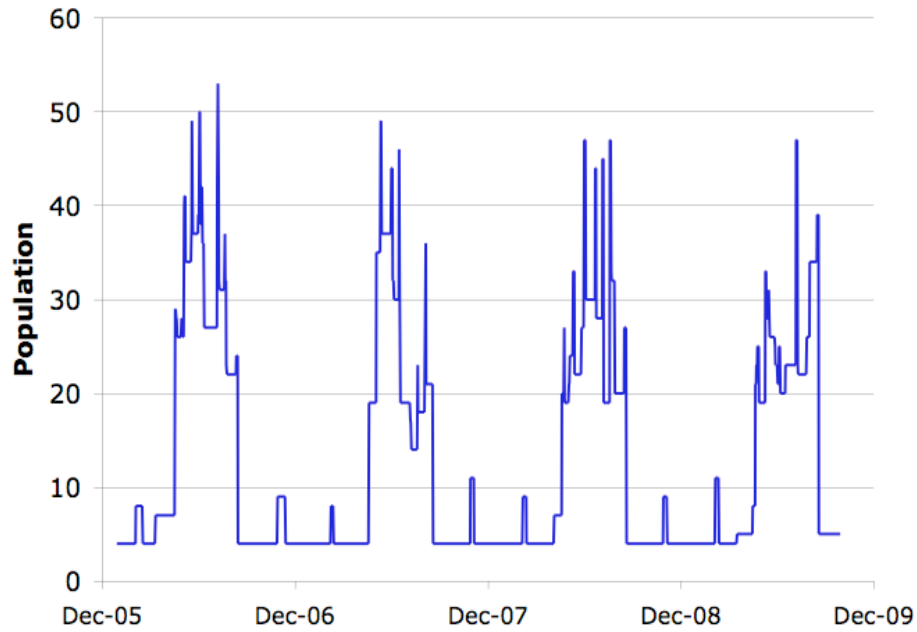
- Minimum annual water withdrawal: 68,000 gallons

- Heat demand (continuous):  $\leq 60$  MBH

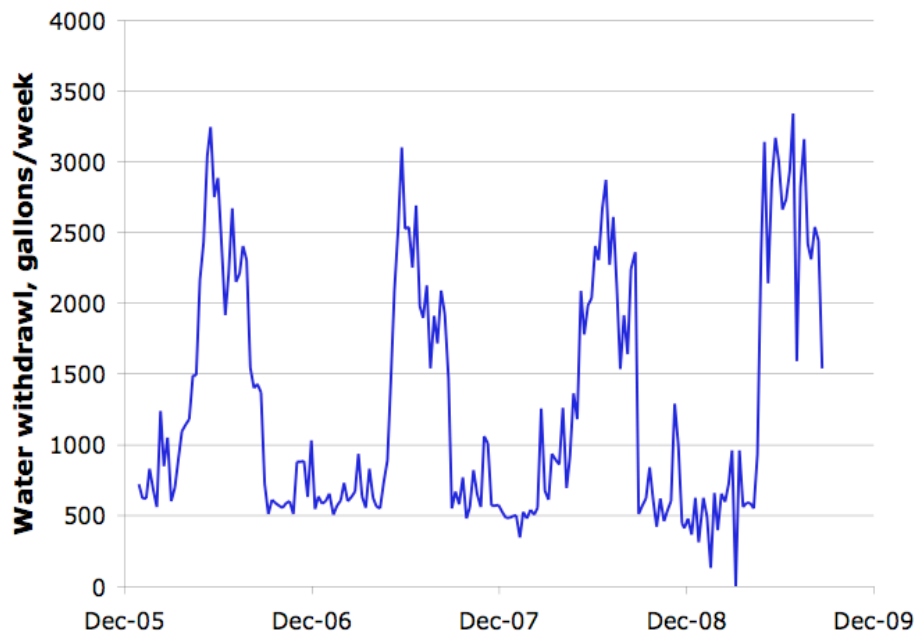
- Heat demand (peak):  $\leq 142$  MBH

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\* These water demand requirements are based on a high estimate of the average weekly water demand shown in Figure 3.1. This would produce an annual withdrawal of 86,771 gals, 25% higher than the minimum requirement.



(a)



(b)

**Figure 3.1.** Recent (a) population and (b) water demands for Summit, Greenland (data provided by Sandy Starkweather, Polar Field Services, Inc. via email 26 Oct 2009).

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Scenario 2: Based on the above information for scenario 2 the following requirements for a water system are:

- Baseline withdrawal duration: 309 days
- Baseline water demand: 756 gal/wk
- Peak withdrawal duration: 56 days (broken into 4 time intervals of 14 days each)
- Peak water demand: 1512 gal/wk
- Annual water withdrawal: 45,468 gallons
- Heat demand (continuous):  $\leq 60$  MBH
- Heat demand (peak):  $\leq 142$  MBH

Furthermore, it is planned that the Model 5 Station would minimize reliance on fossil fuels and use renewable energy sources (e.g. solar heating and wind power) as much as possible. Thus a further requirement for the final design is to minimize energy usage with the aim of reducing the carbon footprint.

## 3.2 Analysis

As discussed in section 2, there are two basic methods for obtaining water at inland Polar Regions, melting surface snow and forming a subsurface water well in the glacial ice (a Rodwell). First we review the performance of existing surface snow melting systems in terms of their energy requirements and other demands and their suitability for meeting the above system requirements. Then we conduct a feasibility study for use of a Rodwell that would meet the above requirements.

*3.2.1 Melting surface snow* – As discussed above, the energy requirement to supply two weeks of water for 6 people using the existing snow melting system is  $60,000 \text{ BTU/hr} \times 48 \text{ hrs} = 2.88 \times 10^6 \text{ BTU}$  and the water demand is 15-18 gallons of water per person per day. A conservative estimate of the energy required would be based on the lesser value (15 gal/person/day) requiring at least 1,300 gallons for a two-week period, resulting in an energy requirement of about 2,300 BTU/gallon of water. This is the “average” energy requirement only associated with melting the harvested snow. The additional energy associated with harvesting the snow is only about 1 BTU/gallon of water and transporting the water is 0.5 BTU / gallon of water (see appendix C) and is therefore negligible. We contrast this to the latent heat of water that is about 17.3 BTU/gallon. This is the minimum amount of energy required to melt the snow into water provided there are no heat transfer losses going from the waste heat glycol loop to the snow, however it is noted that there are significant heat losses in the current system.

*3.2.2. Rodwell* – To estimate the performance of a Rodwell at Summit, Greenland we used computer code developed to design the water well used at the South Pole station (Lunardini & Rand, 1995). The input parameters for the original code were tailored for the South Pole. To use this for Summit, Greenland, determination of the correct inputs for the region was needed, including the firn temperature, firn density with depth, water usage schedule, etc. We enumerate the parameters used in this simulation that apply to the Summit case in Table 3.1.

**Table 3.1.** Input parameters for Rodwell simulations for Summit, Greenland.

Firn Temperature (F)	-20
Maximum heat flow rate (MBH)	142
Glycol temperature from boiler(F)	150 – 190
Mass flow rate through boiler (gpm)	104
Target initial bulb volume (gallons)	12,000 - 13,000
Design lifespan (years)	10
Well depth range (ft)	100 - 600

In addition to the parameters in Table 3.1, we need to know the change in firn density with depth. This controls the volume of water created from the melted void in the firn and determines the depth at which the firn is non-porous, i.e. where melt water is no longer lost into the surrounding firn. We performed a piecewise fit to the available data that gives an adequate estimate of the variation at Summit (see Appendix B):

$$\rho_i \text{ (lbm/ft}^3\text{)} = 20.18 + 2.4996 Z^{0.45}; Z \leq 394 \text{ ft}$$

$$\rho_i = 57.54 \text{ lbm/ft}^3; Z > 394 \text{ ft}$$

This was entered as a condition into the computer code, replacing the curve fit used for the South Pole data.

### 3.2.2.1 Scenario 1

The input conditions for the first scenario are given in Table 3.2. Several cases were run to capture the design space for operating a Rodwell at Summit. Once we established an initial case that would quickly produce initial target bulb volumes, and also operate for a minimum of 10 years, we then varied the parameters to minimize energy usage while still meeting target performance metrics. In Table 3.3 the results of the most informative cases are summarized.

**Table 3.2.** Input conditions for scenario 1.

Duration of summer season (days)	153
Water withdrawal during summer season (gal/day)	430
Duration of winter season (days)	212
Water withdrawal during winter season (gal/day)	100

Case 6, in Table 3.3, is a basic design case that will meet the requirements stated above. This assumes a lower boiler temperature of 150 F, and an initial start-up of 9 days to reach an initial bulb water volume greater than 12,000 gallons. To minimize water loss to the firn, the initial well depth is established at 160 ft below the surface. For this case, start-up and initial operation of the Rodwell takes 95 days. It is anticipated that this start-up period would occur during the last part of a summer season. Since the summer season is about 153 days long, this allows 58 days at the beginning of the first summer to install the equipment for the Rodwell and drill the initial hole. The balance of the summer would then be consumed with well start-up. If the installation period needs to be lengthened,

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further refinements on the calculations can be made at a later time. This first case demonstrates that a Rodwell installation should be feasible at Summit with the available waste heat.

Cases 7-9 explore the viability of operating with lower energy requirements than baseline Case 6. Case 7 required the same heat demand as case 6 to establish the initial well, after that the heat is cut back to require no more energy than the current snow melter system. Based on the melter requiring 2,300 BTU/gallon (see section 3.2.1), and using the withdrawal rates given in Table 3.2, during the summer the melter would require about 41.2 MBH and during the winter it would draw about 9.58 MBH. This case does not provide enough heat to sustain the bulb beyond the first full winter. There is not enough meltwater left in the bulb at the end of the winter to satisfy the summer withdrawal rate and the well collapses at the beginning of the summer season, that is, the amount of water withdrawn exceeds the amount produced, and the bulb is not sustainable.

**Table 3.3** Summary of Rodwell performance calculations for scenario 1. Bold table entries indicate a change in conditions from the previous case.

	Case 6	Case 7	Case 8	Case 9	Case 10
<b>Bulb formation</b>					
Duration (days)	9	9	9	9	9
Boiler heat flow rate (MBH)	142	142	142	142	142
Boiler water temperature (F)	150	150	150	150	<b>190</b>
Initial well depth (ft)	160	160	160	160	160
Bulb water volume (gal)	12186	12186	12186	12186	12254
Water loss to firn (gal)	0	0	0	0	0
<b>Initial water withdrawal</b>					
Duration (days)	86	86	86	86	86
Boiler heat flow rate (MBH)	60	60	60	60	60
Withdrawal (gal/day)	430	430	430	430	430
Bulb water volume (gal)	15923	15923	15923	15923	15979
Total water loss to firn (gal)	657	657	657	657	3339
First summer operation (days)	95	95	95	95	94
<b>First winter operation</b>					
Duration (days)	212	188	212	212	212
Boiler heat flow rate (MBH)	60	<b>9.58</b>	<b>20</b>	<b>40</b>	40
Withdrawal (gal/day)	100	100	100	100	100
Bulb water volume (gal)	73908	127	11158	40953	40999
Total water loss to firn (gal)	657	657	657	657	659
Well depth (ft)	218	218	206	212	212
<b>Summary of operations</b>					
Duration (yrs)	10	1	1.1	10	10
Summer heat flow (MBH)	60	<b>41.2</b>	41.2	<b>40</b>	40
Summer withdrawal (gal/day)	430	430	430	430	430
Duration (days)	153	Collapse	Collapse	153	153
Winter heat flow (MBH)	60	at begin of	at begin of	40	40
Winter withdrawal (gal/day)	100	second	second	100	100
Duration (days)	212	summer	summer	212	212
Bulb water volume (gal)	76411	0	0	30337	30339
Total water loss to firn (gal)	657	657	657	657	659
Well depth (ft)	341	218	244	588	588
Total water withdrawal (gal)	841369	58490	123940	841370	841370

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In Case 8 the available winter heat is increased to 20 MBH, which delays the bulb collapse to partway through the second summer season. In Case 9 we level the summer and winter available heat to 40 MBH, and a sustainable bulb is maintained for 10 years. The final well depth after 10 years is 588 ft. The average power requirement over this 10-year period is 40.29 MBH. This includes start-up and continuous operation. The average amount of energy per gallon is 4,130 BTU/gal.

this case the boiler temperature is increased to the maximum of 190 F. This has minimal impact on the bulb formation and no impact on the final bulb depth. Thus, Cases 9 & 10 demonstrate a viable Rodwell design with energy consumption minimized. Though further refinements / optimizations in this design are possible, this gives an initial operational design.

With this design (Cases 9 / 10), the energy demand on the available waste heat is about 1.8 times higher than the current snowmelt configuration. Whether or not this additional energy can be justified because of its reduction in labor to provide water via snow melting methods is outside the scope of this effort.

### 3.2.2.2 Scenario 2

In this second scenario we determine the feasibility of using a Rodwell for the projected population under Model 5 operations. In this simulation we lump the withdrawals into two categories, baseline (population of 6) and peak (population of 12). To simplify the simulation we implement these as step functions that cycle once per year. Based on the calculations run in scenario 1 we conclude that this simplification is justified. In particular, we find that we maintain the same heat flow both during the summer and winter once the initial well is established, and the bulb that is formed after about 1 year of service is enough to satisfy about a half year of operation (see Table 3.3, cases 9 & 10). As a result increased withdrawal rates that occur intermittently throughout the year have roughly the same effect as one continuous increased withdrawal period, and there is enough storage in the system to accommodate these fluctuations. Actual physical operation of the well would require detailed adjustments to accommodate these periodic withdrawals, but these are not captured in the physics of the computer code and therefore would have no effect on the model outcome. In Table 3.4 we provide a summary of the duration and withdrawal rates for the baseline and peak “lumped” periods.

Another consideration in this scenario is the start-up period. We assume that the population during well start-up is elevated to accommodate the crew needed to start the well and that this operation will occur during transition from the existing station to the Model 5 operation. As such we have the same start-up conditions as for scenario 1 (e.g. water withdrawal rate and period, heat flow rate, etc.)

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**Table 3.4.** Input conditions for scenario 2.

Duration of start-up (days)	95
Start-up withdrawal (gal/day)	430
Duration of baseline withdrawal (days)	309
Baseline withdrawal (gal/day)	108
Duration of winter season (days)	56
Water withdrawal during winter season (gal/day)	216

**Table 3.5.** Summary of Rodwell performance calculations for scenario 2. Bold table entries indicate a change in conditions from the previous case.

	Case2.1	Case 2.2	Case 2.3	Case 2.4	Case 2.5
<b>Bulb formation</b>					
Duration (days)	9	9	9	9	9
Boiler heat flow rate (MBH)	142	142	142	142	142
Boiler water temperature (F)	150	150	150	150	150
Initial well depth (ft)	160	160	160	160	160
Bulb water volume (gal)	12186	12186	12186	12186	12186
Water loss to firn (gal)	488	488	488	488	488
<b>Initial water withdrawal</b>					
Duration (days)	86	86	86	86	86
Boiler heat flow rate (MBH)	60	60	60	60	60
Withdrawal (gal/day)	430	430	430	430	430
Bulb water volume (gal)	15923	15923	15923	15923	15923
Total water loss to firn (gal)	657	657	657	657	657
First summer operation (days)	95	95	95	95	95
<b>Completion of First year operation</b>					
Duration (days)	309	309	309	309	309
Boiler heat flow rate (MBH)	40	<b>30</b>	<b>35</b>	<b>25</b>	<b>20</b>
Withdrawal (gal/day)	108	108	108	108	108
Bulb water volume (gal)	46346	25953	35897	16706	8530
Total water loss to firn (gal)	657	657	657	657	657
Well depth (ft)	217	214	215	212	212
<b>Summary of operations</b>					
Duration (yrs)	10	10	10	10	10
Peak withdrawal heat flow (MBH)	40	<b>30</b>	<b>35</b>	<b>25</b>	<b>20</b>
Peak withdrawal (gal/day)	216	216	216	216	216
Duration (days/yr)	56	56	56	56	56
Baseline withdrawal heat flow (MBH)	40	<b>30</b>	<b>35</b>	<b>25</b>	<b>20</b>
Baseline withdrawal (gal/day)	108	108	108	108	108
Duration (days)	309	309	309	309	309
Bulb water volume (gal)	43754	19035	29672	11162	5495
Total water loss to firn (gal)	657	657	657	657	657
Well depth (ft)	301	362	324	433	632
Total water withdrawal (gal)	477442	477442	477442	477442	477442

Five cases were run for this scenario and they are summarized in Table 3.5. The first case (2.1) is essentially the same as case 9, scenario 1 except that the withdrawal rates and durations after the well is established are changed to meet the demands for the projected population for Model 5 operation. The remaining four cases explore the effect of reducing the heat flow on well performance. Table 3.5 shows that in all five cases a Rodwell can be established and maintained for a full 10 years, even with reduced heat flow (from 40MBH to 20 MBH). However the “steady” bulb water volume for the cases 2.4 & 5 once “steady” operations are established is very small leaving very little buffer if the well water production needs to be stopped for a short period. For example, at baseline withdrawal and a heat rate of 20 MBH (Case 2.5) the amount of water stored in the bulb

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at the end of the first year of operation would last less than 80 days if there were no freeze-back (progressive freezing of the water bulb due to loss of heat flow to the well). Due to freeze-back the usable water amount would be significantly less. Thus, operation with such small water bulb volumes is not recommended. Furthermore, the final well depth for lower heat flows is much deeper (632 ft for a sustained 20 MBH vs. 301 ft for 40 MBH). Thus, these low heat flow rates produce a deep, narrow well, rather than the preferred wide, shallow well. From an operational point of view, the narrow deep wells require more attention as more piping needs to be fed down the well hole and the frequency of lowering the pump assembly increases. Also with the increased depth, annual pump changes are more labor intensive as more pipe is required. Therefore, the optimal heat flow rate is likely in the range of 30-40 MBH. Further design work will be required once the detailed requirements for the Model 5 design operation are established to determine a final optimized well design.

Using the results for cases 2.1-2.3 (30 – 40 MBH) the average heat required per gallon of water is 6,600 – 7,500 BTU/gal. This is 1.7 times higher than scenario 1 and 3.0 times higher than the current method used to harvest and melt snow. This increase in specific heat usage for scenario 2 over scenario 1 is a result of more heat loss to the surrounding firm and air per unit volume of the water bulb for the smaller water bulb established in scenario 2 in comparison to scenario 1. This shows that the Rodwell is better suited to handling large populations, and as the population shrinks the efficiency of the Rodwell declines.

*3.2.3 Other considerations* – The above discussions show that a Rodwell could be established and successfully operated based on the existing available heat at Summit Station and the assumptions provided in Table 3.1 are met. Additional considerations that need to be addressed in the design of a Rodwell for this application are available electrical power, resources and contingency. We will discuss each of these in turn.

First, based on the Rodwell design used at South Pole the power consumption to operate the pumps, heat tape and other electrical components to support the Rodwell is about 20kW. This may be higher than what is needed for the smaller installation required at Summit. However, such power requirements will need to be factored into the overall design of the Model 5 station if the Rodwell is to be considered.

Establishment of a Rodwell requires that resources and personnel need to be available specifically to support that operation. The time to install the equipment and establish the initial bulb will take at least a month. It is recommended that there is an overlap in systems during the initial year of operation so that a sufficient reserve of water is generated in the well before cutting over to Rodwell-only use. Once the well is established, daily monitoring of the well is required to maintain proper performance. Annually the pump assembly should be swapped out. This should be done during the summer months when there is sufficient crew to support this effort. This takes 2-4 days and requires a crew of 3-4 people to accomplish.

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Another factor to consider is placement of the Rodwell. Information regarding subsurface waste (including old sewage outflows) and / or debris (including buried buildings and equipment) must be determined so the Rodwell can be established in an area free of waste or debris over its entire life cycle. Determination of the location of subsurface waste and debris may be possible through a ground penetrating radar (GPR) survey.

In the event that the heat supply is cut off for the Rodwell, a back-up boiler needs to be available to maintain the heat circulation to the bulb. If no heat is available for an extended period of time, the pump unit will need to be drawn up out of the water bulb to prevent freezing the pump into the resulting ice that would form. This requires 3-4 people to be on hand to draw the pump up 8-10 feet out of the water and into the air (John Rand, Pers. Comm., 2010).

#### 4. Conclusions

In this study we reviewed methods used in Polar Regions to provide potable water that may be applicable for use at Summit, Greenland. We found that two predominate methods are used, melting surface snow and melting subsurface ice to form a well and extracting the melt water to the surface (a Rodwell). Of these two methods, melting surface snow is most widely used and is currently used at Summit Station.

There is limited published data on the energy usage for melting surface snow. For this analysis we rely mainly on data from the existing Summit Station. The basic energy requirement to melt snow is about 2,300 BTU/gal. This does not include the energy associated with harvesting the snow or transporting the water after it is melted, both of which are labor-intensive activities requiring use of heavy equipment. Also, there is additional labor associated with transfer of the melt water from the melt tank to the transportation tank and then to the final storage tank. There are opportunities to reduce the labor in this process with a new design of the system (e.g. piping water from the melt tank to the point-of-use locations).

We also reviewed the feasibility of using a Rodwell at Summit. There is sufficient ice depth to support such a system, thus providing opportunities to reduce the labor associated with acquiring the “feed stock” for the meltwater and to improve the water quality at Summit Station. In this case, a subsurface well would be established in the ice sheet and meltwater from the well would be pumped to the surface for treatment and distribution to point-of-use locations. The approximate sustained energy requirement for this system would be 30 - 40,000 BTU/hr, with an initial requirement of 142,000 BTU/hr for bulb start-up. These energy requirements are well within the available waste heat at the current Summit Station, however considerations should be made for the anticipated decrease in available waste heat with the construction and implementation of Model 5. This feasibility study shows that a Rodwell can provide at least 10 years of service before it will need to be re-located. Depending on the population that the well will need to support, the energy requirement for this system is about 4,100 to 7,000 BTU/gal or 1.8 to 3.0 times higher than the current system of melting surface snow. The lower the population, the higher the specific energy required to generate water is, thus the Rodwell

becomes less attractive from an energy consumption point of view as the population gets smaller.

## 5. References

Armstrong, R.S (2010). Summit Station Energy Survey. Report prepared for Arctic Research Support and Logistics, NSF.

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APPENDIX A: Summary of existing methods for providing potable water at polar stations

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Location	Years active	Type of system	Population	Production level	Treatment	Transport System To Production	Water Transport once Potable	Other	References
Neumayer Station III	2009-present	snow melting	10 winter; 58 summer	117 L/person/day	??	Taken from surface to the east of the station and pushed through a chute into the melting vessel. An 'automatic' drift snow collector has been devised and may prove helpful in reducing the effort for snow transport.	pipd	Melter will be driven by excess heat from the diesel generators; Nominal capacity of the melter will be in the range of 25 kW	18, various web
Halley VI, Antarctica	2008 - present	snow melting	16 winter; 52 summer	??	??	Vehicles will be used to fill the station melt tanks with snow	pipd	Both energy modules will include solar thermal panels to supplement the waste heat collected from CHP generator engines for water heating. Evacuated tube solar panels will be positioned on the vertical surfaces of the energy modules.	17, various web
Princess Elisabeth Antarctica, Dronning Maud Land, Antarctica	2008 - present	snow melting	12 winter; 48 summer	??	anaerobic reactor, filtration, aerobic bio-reactor, active carbon, chlorination unit, and finally a regeneration system using UV treatment for conservation of drinking water inside the tank	utilization of snow drifting around station and ridge; collected snow will be automatically dumped into the (lower positioned) snow collector; When snow accumulation is low a tractor will be used	pipd	100% of used water is recycled, 75% is used a second time, all recycled water is used for non-potable applications; use solar thermal panels for snow melt	2,16
Troll Station	2005-present	snow melting (winter) and fresh water reservoir (summer)	8 winter; 40 summer	??	??	??	??	During summer use reservoir of freshwater melted below blue ice	18,
Concordia, Dome C	2004-present	snow melting	15 winter; 70 summer	400 L/day in recycling system; 1188 L/day snow melting	various	??	??	energy to melt snow is produced by using a cogeneration system connected to the main electrical diesel generators	various web
Vostok Station	1999/2000	solar heating facility	n/a	~2 gal/hour	??	Snow is loaded into the collector via tractor	??	The concentrator is automatically oriented towards the sun where the rays are concentrated on the absorber and the solar heat is effectively transported from the absorber to snow through the heat transferring system.; Production is max based on tests done at -35 C and 3-4m/s winds	13,
South Pole Station, Antarctica	post 1995	Rodwell	28 winter; 140 summer	530,000 gal/yr	yes	melted in-situ - NO TRANSPORT NEEDED	??	Rodwell started to be tested in 1993 and took a few years to move completely to this system	14,

South Pole Station, Antarctica	pre 1995	snow melting	??	25 gal/man-day summer;	filtered through diatomaceous earth and treated with baking soda to combat oily taste	Front end track loader made continuous 45 min. round trips to four snow melters	??	heated by exhaust gases from the diesel generators (required 14.6 tons of snow/day)	1,14
Hallett Station	pre 1969	natural melting	??	??	??	melted in-situ - NO TRANSPORT NEEDED	water is collected in basin and piped down a slope till it fills waiting water wagons - wagons haul the water to various buildings and pump into storage tanks	In the winter they use distillation	12,
McMurdo Station	pre 1965	snow melting	250 winter; 1100 summer	20 gal/person/day	filtration using a vacuum diatomite filter then chlorinated	tractor and scoop goes out 1/2 mile from station	Water is distributed to storage tanks in buildings through a 1" hose, once/day; Buildings more than 150' away use bottled drinking water; each building has its own melter for water for other uses		12,
NCEL camp, Ross Ice Shelf, Antarctica	winter 1964/65	snow melting	20	12 gal/man-day	2, 5-micron particle filter elements of resin-bonded cellulose fiber; 18 activated carbon cartridge elements for removing taste and odor	loaded with a 2 yd3 bucket on a front-end loader	Pneumatic pressure system distributed the water to the fixtures; Storage tanks has 350 gallon capacity	water from the melter tank was circulated through an oil-fired water heater and returned to the melter reservoir	1,3,
DYE 2 and DYE 3, Greenland	~1960-1980	snow melting	30	2000 gal/day	??	snow is hauled up to the building (19 ft elevation) by remote control using a fixed dragline which tips into a projecting hopper; requires about 1 hr operation per day to fill the melter tank with enough snow	transfer pump takes usable water from the tank for distribution inside the heated composite building by a hydropneumatic system	Snow is sprayed with warm water from nozzles; spray water is heated by waste heat from the generating engines	1,7,
"New" Byrd Station, Antarctica	1960s	snow melting	??	25 gal/man-day summer; 10 gal/man-day winter	filtered through diatomaceous earth	carted by sled (from 1/4 mile upwind); then loaded by an inclined conveyor belt	distributed from a loop circulating continuously	heat exchanger on the cooling system provides energy for melting	1,12
Tuto under ice camp, Greenland	1960s	snow melting	??	??	??	melted in-situ - NO TRANSPORT NEEDED	??	continuous circulation of water from the well and through heat exchangers fitted to the station power plant	1,
Point Barrow Camp	1960s	fresh-water lake	??	26,000 gal/day for Aug. 1963	3, Army-type pressure filters and chlorination (Drinking water only)	Pumped to camp	Pumped to individual buildings		12,
Camp Century, Greenland	1959/1960	water well	??	10,000 gal/week	chlorination of 1 ppm	n/a	pipng	vertical shaft steamed through snow to ~140-160' down where ponding occurred	1,
Syowa Base	1956-62	snow melting	11 winter; 40 summer	~5.25 gal/person/day	none	Pure ice dug out of an iceberg	originally by hand then later by pump	uses recovered exhaust-gas heat of the diesel engines and a steel walled melting tank	4,
NCEL camp, Ross Ice Shelf, Antarctica	1963	electric immersion heaters	25	??	??	??	??		1,3,

Camp Fistclench (Site II), Greenland	1957	snow melting	??	??	??	10-ton sleds; system was underground so just had a hopper	piped and 5 gal cans	Melted in 2 tanks heated by kerosene burners	1,
Camp Fistclench, Greenland	1957	water well	??	??	??	n/a	??	vertical shaft steamed through snow to ~130' down	1,
Little America V, Ross Ice Shelf, Antarctica	1956	snow melting	??	??	??	shoveled manually	pumped to overhead storage; some pipe distribution	melted in the tank by circulating warm water	1,
USAF ice cap radar station N-33	1952	snow melting	118 max	15-25 gal/day/man	??	bladed into a 5ft diam. Chute	snowmelter was 500 yards from camp - barrels mounted on sleds to take water to storage tanks	Cleaver Brooks snowmelter; Water samples taken to Thule regularly for testing	4,
USAF ice cap radar station N-34	1952	snow melting	20	450 gal/hour	??	bladed into a 5ft diam. Chute	snowmelter was 500 yards from camp - barrels mounted on sleds to take water to storage tanks	Cleaver Brooks snowmelter; Water samples taken to Thule regularly for testing; independently heated melt tank; fire tubes passed through melter and warm water was sprayed over the snow from header tubes above; passed to storage tank	1,4

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## APPENDIX B: Method for predicting performance of Rodwell at Summit, Greenland

### B.1 Model description

We adapted the computer code developed by *Lunardini & Rand* (1995) to compute the performance of a proposed Rodwell for Summit station. This code assumes that a bulb formed in the firn is a paraboloid below the water line and a cone above the water line up to the starting depth of the well. The shaft for the well is a cylinder from the starting point to the surface. The melting of the firn is a result of warm water being pumped down to the bottom of the initial shaft. The bulb grows laterally and in depth as the melting proceeds. The program tracks the following energy balance

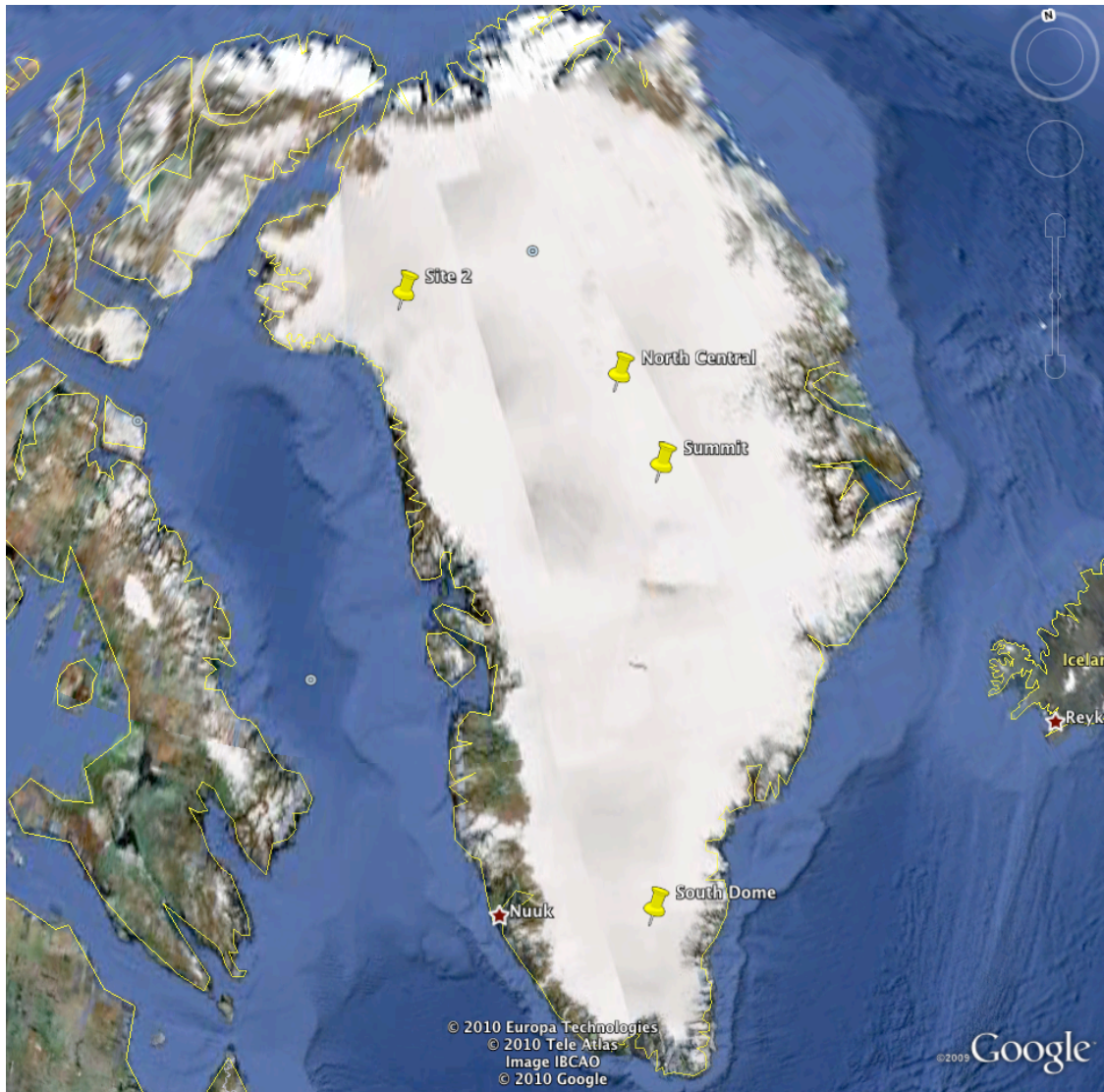
$$E_m = E_w - E_{cf} - E_{wa} \quad (A.1)$$

where  $E_m$  is the energy that goes into melting and producing water from the firn,  $E_w$  is the energy available in the warm water,  $E_{cf}$  is the energy loss due to conduction into the firn, and  $E_{wa}$  is the energy lost due to convection from the free water surface into the air in the bulb / shaft. The amount of energy that remains melts ice (firn) and produces water. However some of the water is lost to the surrounding porous firn, thus not all of the water generated is available to be withdrawn from the well. The rate of water loss to the surrounding firn is a function of the firn porosity, which is also a function of depth.

According to *Lunardini & Rand* (1995), the density at which all water loss is stopped is 45 lbm/ft<sup>3</sup> (0.72 g/cc). The surface snow density near Summit reported by several sources is around 0.25-0.35 g/cc (*Herron & Langway* 1980, *Dibb & Fahnestock* 2004, *Hawley et al.* 2008). Consequently information about the variation of firn density with depth is required to compute the water lost to the surrounding firn. *Herron & Langway* (1980) provide density / depth data down to about 70 m for 3 locations in Greenland named “Site 2”, “South Dome” and “North Central.” Their approximate locations are shown in Figure A.1. The depth at which the firn density was 45 lbm/ft<sup>3</sup> at these three sites ranged from 40-50m, so there is some variability in the density with depth at the various sites. Thus, it is desirable to get the depth / density information at Summit.

*Hawley et al.* (2008) measured the density to a depth of 30 m at Summit Station. Unfortunately this depth was not deep enough to reach a density of 45 lbm/ft<sup>3</sup>. Thus, to determine an approximate depth / density relationship we used information from both the *Herron & Langway* (1980) and *Hawley et al.* (2008). This is provided as eq. (3.1). This is adequate for this feasibility study, though better data would be desirable if a detailed analysis is warranted.

The complete computer code used for this simulation is printed out at the end of this appendix.



**Figure A.1.** Map of Greenland with approximate locations (push pins) of measurements of firn density down to a depth of 30m or more.

## B.2 References

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Herron, M.M. and C.C. Langway (1980) Firn densification: an empirical model. *J. Glac.* **25**:93.

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Lunardini, V.J. and J. Rand (1995). Thermal Design of an Antarctic Water Well. *CRREL Special Report 95-10*.

B.3 Computer Code “Summit.f”

DRAFT

```

program main

c Original program written for
c   Lunardini, V. J. and J. Rand (1995) Thermal Design of an Antarcti
c Water
c   Well, CRREL Special Report 95-10, Cold Regions Research and Engin
c eering
c   Laboratory, Hanover, NH.

  IMPLICIT DOUBLE PRECISION (A-H,K-M,O-Z)
  character PRNTR*12
  integer i,j,n

  integer jj

  read(*,*) PRNTR
  OPEN(9,FILE=PRNTR, STATUS='unknown')

c
c Modified to run for Summit, Greenland

CCC  FORMATION DELT = TZ3
  read(*,*) TZ3 ! hrs
  read(*,*) MG0 ! gallons, initialized bulb volume
  read(*,*) QBC
  read(*,*) MF !lbm/hr, Boiler mass flow rate
CCC  PHASE 1 1ST SUMMER DELT = TZ4+24
  read(*,*) TZ4 !hrs
  read(*,*) QBC1 ! btu/hr
  read(*,*) MUG1 ! gal/day, initial withdrawal
  read(*,*) MF1 ! lbm/hr, boiler mass flow rate
  TZ3E = 88000.0 ! ten years
CCC  PHASE 2 1ST SUMMER DELT = TZ5
  read(*,*) TZ5 ! hrs
  MUG2 = MUG1 ! gal/day
  read(*,*) QBC2
  read(*,*) MF2
CCC  PHASE 3 1ST WINTER DELT = TZ6
  read(*,*) TZ6
  read(*,*) QBC3
CCC  2ND & SUB SUMMERS
  read(*,*) QBC4
CCC  2ND & SUB WINTERS
  read(*,*) QBC5

  AL = 0.30 ! Firn loss parameter
  ALPHAI = .0446 ! ft2/hr
  BO = 1.1
  CPA = .24 ! BTU /lb-F, Cp air
  CPI = .5 ! Cp ice

```

```

CPW = 1.0 ! Cp water
read(*,*) DEPTH ! ft, initial depth to top of water
DT = 8.333001E-03 ! hrs (30 secs)
EIT = 0.0
E = 0.0
FI = 0.90
GAM = 1.0
H = 10.0
HA = 1.0
HB = 60.0
HI = 1.0
HS = 32.5 ! BTU/hr-ft2-F
HBN = 24.0
HSN = 32.5
HSO = 32.5
J = 1
KI = 1.28 !BTU/hr-ft-F, ice/firn conductivity

MU = 0.0
MUD = 7549.5
MWG = 0.0 ! gallons, bulb water volume in gallons
read(*,*) MFS ! summer boiler flow rate. lbm/hr
read(*,*) MFW ! winter flow rate
read(*,*) MUGS ! summer withdrawal, gal/day
read(*,*) MUGW ! winter withdrawal, gal/day
MGW = 1106533.0 !
N = 1
OMEGA = 5.399
PI = 3.141593
PL = 0.0
PM = 0.0
PLT = 0.0
PMT = 0.0
PRWT = 0.0
QS = 0.0
QT = 0.0
QTT = 0.0
QIT = 0.0
RA = 1.5 !ft, drill radius
RHOIS = 45.0 !lbm/ft3, start close-off density of firn
RHOIM = 57.54 !lbm/ft3, max firn density
RHOW = 62.6 ! lbm/ft3, water density
RO = RA ! ft

```

#### CCC TIME PARAMETERS

```

TAUP = 0.0
TI = 0.0
TIS = 0.0
TP = 24.0
TPI = 24.0

```

```

TPIW = 24.0
TZ1 = 8760.0 ! 8760 days is one year
TZ2 = 8760.0
TZS = TZ1 - TZ6 ! Summer duration (days)

CCC  TEMPERATURES

TF = 32.0
read(*,*) TICE ! F, Firn Temperature
read(*,*) TWB ! F, Boiler water temperture
TA = TICE
TS = TICE
TW = TWB

! depth at which shut-off starts in firn.
ZS = ((RHOIS - 20.18)/2.4996)**(1/0.45) ! Greenland data

ccc
D = 2.82843*RO !ft, diameter of bulb
MFA = MF
MW = PI * RA * RA * H * RHOW !lbm, water mass
MWO = MW
HWB = DEPTH + H !ft, depth to well bottom
MWGA = MW / (.134 * RHOW) ! gallons, convert bulb water mass to v
olume in gallons
LE = 144.0 + CPI * (TF - TICE) * OMEGA
AB = PI * D**2./4.0 ! ft2, air-water interface area
HW = H ! ft, water depth
AS = 2.0*PI*D*H/3.0 ! ft2, water-ice contact area
VW = PI*D**2.*H/8.0 ! ft3, water volume in bulb
AI = 2.0 * PI * RA * DEPTH ! ft2, air-ice contact area
VA = PI * RA * RA * DEPTH ! ft3, air volume

130  Write(9,3000)
3000  format(1x, '          ANTARCTIC PARABOLIC ICE RESEVOIR FORMATION '
)
140  Write(9,3001) TWB
3001  format(1x, ' BOILER WATER TEMP DEG F              = ',F9.2)
150  Write(9,3002) MF
3002  format(1x, ' BOILER WATER FLOW RATE lbm/hr          = ',F9.2)
160  Write(9,3003) HS
3003  format(1x, ' CONVECTIVE COEFFICIENT BTU/HR-FT2-F      = ',F9.2)
Write(9,3013) RA
3013  format(1x, ' INITIAL DRILL RADIUS FT                = ',F9.2)
Write(9,3014) DEPTH
3014  format(1x, ' DEPTH TO TOP OF WATER AT START FT        = ',F9.2)
180  Write(9,3005) D
3005  format(1x, ' INITIAL PARABOLIC WATER DIAMETER D FT    = ',F9.2)
191  Write(9,3007) HW
3007  format(1x, ' INITIAL PARABOLIC WATER HEIGHT HW FT     = ',F9.2)
200  Write(9,3008) TW
3008  format(1x, 'INITIAL WATER TEMP TW DEG F              = ',F9.2)

```

```

201  Write(9,3009) TA
3009  format(1x,' INITIAL AIR TEMP TA DEG F' = ',F9.2)
202  Write(9,3010) TS
3010  format(1x,' INITIAL ICE SURFACE TEMP TS DEG F' = ',F9.2)
210  Write(9,3011) TICE
3011  format(1x,'AMBIENT ICE TEMP DEG F' = ',F9.2)
220  Write(9,3012) LE
3012  format(1x,'EFFECTIVE LATENT HEAT BTU/LB' = ',F9.2)

221  Write(9,*) 'TIME IN HRS, WATER VOL MW GALLONS, ICE AREA AI FT2,
& AIR VOL VA FT3 '
222  Write(9,*)
252  Write(9,*) ' TIME TW TA TS MW D HW H
WB
& AI VA'
253  Write(9,2001) TI, TW, TA, TS, MWGA, D, HW, HWB, AI, VA
3030  format(1x,F8.2, 3F7.2,F9.2,2F6.2,F7.2,2F7.2)

260  DO I=1,112500000
      IF (MWG .GT. MGO) GOTO 1220 ! bulb water volume .gt. initilaiz
e volume
      IF (TI .GT. TZ3) GOTO 1220 ! time .gt. formation period
      IF (J .EQ. 1) GOTO 280 ! not sure why we branch here, bul
b formation?

400  IF (TI .LT. TAUP) then ! not sure what taup is
      MF = 0.0
      MUG = MUGA
      MU = MUD
    else
      MF = MFA
      MUG = 0.0
      MU = 0.0
    end if

! determine firn density
280  ZP = HWB-H/2.0 ! ft, average bulb depth
! This is for Greenland data at Summit
RHOI = 20.18 + 2.4996 * ZP**0.45 ! shallow: ZP .le. 394 ft
IF(ZP .GT. 394) then
  RHOI = RHOIM
end if

! compute the change in water depth, h (eq. 7)
291  DELH = 16.0*H*(HS*(TW-TF)-QS)*DT/(RHOI*LE*3.0*(2.0*GAM*H+D))
HP = H+DELH
DP = D+GAM*DELH
HWBP = HWB+DELH

! assumes full shut-off of water leakage into firn at ZS.
ZPS = HWB-ZS

```

```

        ASP = 2.0*PI*D*H/3.0      ! all of surface area in fully porous f
irn
        IF(ZPS .GT. H) then      ! bulb below firn shut-off
            ASP = 0.0              ! none of bulb surface area in fully po
rous firn
        else IF(HWB .GT. ZS) then ! well bottom is deeper than firn sh
ut-off
            ZPP = (ZS+HWB-H)/2.0 ! average depth of portion of bulb in
porous firn
            ASP = 2.0*PI*D*H*(1.0-(ZPS/H)**1.5)/3.0 ! portion of bulb i
n porous firn
            RHOI = 20.18 + 2.4996 * ZPP**0.45 ! firn density
        endif
283     MUL = AL*ASP*(RHOIS - RHOI) ! water mass lost to firn

        IF(MF .EQ. 0.0) GOTO 284
284     TWB = QBC/(CPW*MF) + TW
        TWP = TW+(MF*(TWB-TW)-HS*AS*(TW-TF)*(1.0/CPW+(TW-TF)/LE-QS/
&         (LE*HS))-HA*AB*(TW-TA)/CPW)*DT/MW
        MWP = MW+(((TW-TF)*HS-QS)*AS/LE-MU-MUL)*DT
        MWG = MWP / (.134 * RHOW)
        VWP = MWP / RHOW
        HF = SQRT(8.0*VWP*HP/PI)/DP
        DF = DP*SQRT(HF/HP)
        HW = HF
        EP = CPW * (TWB - TWP) * MF * DT
        E = E + EP
        PMP = MU*DT
        PM = PM + PMP
        PLP = MUL*DT
        PL = PL + PLP
        AIP = AI+PI*(DP**2-D**2)/4.0 + PI*DP*(HP-HF)
        VAP = VA + PI*(DP**2*HP-DF**2*HF)/8.0
        H = HF
        D = DF
        TI = DT + TI
        Q = HI * (TA - TS)
        QI = Q * DT * AI
        QT = QT + Q * DT
        QIT = QIT + QI
        QB = QT / TI
        TAU = ALPHAI * TI / (RO ** 2)

        RHOA = 39.685 / (TA + 460.0)
        TAP = TA+(HA*AB*(TW-TA)+HI*AI*(TS-TA))*DT/(RHOA*VA*CPA)

418     FB = 5.0*BO**3.0/36.0-BO/4.0+1.0/9.0+(1.0/3.0-BO/2.0)*LOG(BO)-
&         TAU*(BO-1.0+LOG(BO))
        FBP = 5.0*(BO**2)/12.0 - .25-LOG(BO)/2.0+(1.0/3.0-BO/2.0)/BO-
&         TAU*(1.0+1.0/BO)

```

```

        BP = BO - FB /FBP
        BZ = ABS(BP - BO)
        IF(BZ .lt. .0001) GOTO 425
        BO = BP
        GOTO 418
425      B = BP
        BO = BP +.1
        TS = TICE+QB*RO*(B-1.0)*LOG(B)/(KI*(B-1.0+LOG(B)))
        IF(J .EQ. 1) GOTO 1031
        IF(TI .gt.TPW) GOTO 1130
1028     IF(TI .gt. TP) GOTO 1131
        GOTO 560
1031     IF(TI .gt. TP) GOTO 1128
560      continue
        HWB = HWBP
        TW = TWP
        TA = TAP
        MW = MWP
        AS = 2.0*PI*D*H/3.0
        AB = PI*D**2/4.0
        AI = AIP
        VA = VAP
        IF (D .GT. 60.0) GOTO 1010
        HS = HSO
        GOTO 1040
1010     HS = HSN
1040     IF(TW .LT. 32.0001) GOTO 1075
1041     IF(TI .GT. TZ2) GOTO 1220
        IF(TI .GT. TZ1) GOTO 1220

1070     end do
        GOTO 1760
1075     TW = 32.0
        GOTO 1041
1128     Write(9,2001) TI, TWP, TAP, TS, MWG, D, HW, HWBP, AIP, VAP
        TP = TP + TPI
        TPW = TP
        GOTO 560
1130     Write(9,2001) TI, TWP, TAP, TS, MWG, D, HW, HWBP, AIP, VAP
2001     format(1x, F8.1, 3F7.2, F9.1, 2F6.2, F7.2, 2F11.2)
        TPW = TPW + TPIW
        GOTO 1028
1131     TP = TP + TPI
        TAUP = TP+MUGA*.134*RHOW/MUD-TPI
        GOTO 560
1220     Write(9,2001) TI, TWP, TAP, TS, MWG, D, HW, HWBP, AIP, VAP
2000     format(1X,6F9.2)
1280     Write(9,*)
        EI = E - EIT
        ESR = EI/(TI-TIS)
        EIT = E

```

```

PRW = MW-MWO + PM
PRWT = PRWT+PRW
PLT = PLT+PL
PMT = PMT+PM
EKT = PRWT*19500.0/E
EK = PRW * 19500.0 / EI
PMG = PM/(.134*RHOW)
PM = 0.0
PLG = PL/(.134*RHOW)
PL = 0.0
MWO = MW
EF = E / 140000.0
EFI = EI / 140000.0
QITI = QIT - QTT
QTT = QIT
1340 Write(9,3040) E
3040 format(1x, ' TOTAL ENERGY INPUT BTU = ',E15.6)
Write(9,3041) EI
3041 format(1x, ' SEASONAL ENERGY INPUT BTU = ',E15.6)

Write(9,3051) EFI
3051 format(1x, ' SEASONAL ENERGY INPUT GAL FUEL = ',F15.2)
Write(9,3042) ESR
3042 format(1x, ' SEASONAL ENERGY RATE BTU/HR = ',F15.2)
1370 Write(9,3050) EF
3050 format(1x, ' TOTAL ENERGY INPUT GAL FUEL = ',F15.2)
Write(9,3063) EKT
3063 format(1x, ' AVERAGE LB. WATER PER LB. FUEL = ',F15.2)
1400 Write(9,3060) EK
3060 format(1x, ' SEASONAL LB. WATER PER LB. FUEL = ',F15.2)
1401 Write(9,3070) QIT
3070 format(1x, ' ENERGY FROM AIR TO ICE BTU = ',E15.6)
Write(9,3071) QITI
3071 format(1x, ' SEASONAL ENERGY LOSS, AIR TO ICE BTU = ',E15.6)
Write(9,3064) PMT/(.134*RHOW)
3064 format(1x, ' TOTAL WATER WITHDRAWN GAL = ',F15.2)
Write(9,3061) PMG
3061 format(1x, ' SEASONAL WATER WITHDRAWN GAL = ',F15.2)
Write(9,3065) PLT/(.134*RHOW)
3065 format(1x, ' TOTAL WATER LOSS GAL = ',F15.2)
Write(9,3062) PLG
3062 format(1x, ' SEASONAL WATER LOSS GAL = ',F15.2)

1430 Write(9,*)

```

```

IF(N .EQ. 1) GOTO 1490
IF(N .EQ. 2) GOTO 1204
IF(N .EQ. 3) GOTO 1540

```

```

CCC ***** END OF YEAR 1 *****

      IF(N .EQ. 4) GOTO 1520
      IF(N .EQ. 5) GOTO 1500
CCC ***** END OF YEAR 2 *****

      IF(N .EQ. 6) GOTO 1520
      IF(N .EQ. 7) GOTO 1500
CCC ***** END OF YEAR 3 *****

      IF(N .EQ. 8) GOTO 1520
      IF(N .EQ. 9) GOTO 1500
CCC ***** END OF YEAR 4 *****

      IF(N .EQ. 10) GOTO 1520
      IF(N .EQ. 11) GOTO 1500
CCC ***** END OF YEAR 5 *****

      IF(N .EQ. 12) GOTO 1520
      IF(N .EQ. 13) GOTO 1500
CCC ***** END OF YEAR 6 *****

      IF(N .EQ. 14) GOTO 1520
      IF(N .EQ. 15) GOTO 1500
CCC ***** END OF YEAR 7 *****

      IF(N .EQ. 16) GOTO 1520
      IF(N .EQ. 17) GOTO 1500
CCC ***** END OF YEAR 8 *****

      IF(N .EQ. 18) GOTO 1520
      IF(N .EQ. 19) GOTO 1500
CCC ***** END OF YEAR 9 *****

      IF(N .EQ. 20) GOTO 1520
      IF(N .EQ. 21) GOTO 1500
CCC ***** END OF YEAR 10 *****

      IF(N .EQ. 22) GOTO 1760

1490  MGO = MGW
      MF = MF1
      MUGA = MUG1
      N = N + 1
      J = J + 1
      JJ = 1 ! year
      MFA = MF
      TIS = TI
      TP = INT(TI/24.0)*24.0+TPI
      TZ1 = TP+TZ4
      TZ2 = TZ1+TZ5

```

```

        TZ3 = TZ3E
        QBC = QBC1
        GOTO 1210
1500    MGO = MGW
        MUGA = MUGW
        MFA = MFS
        N = N+1
        MU = MUD
        TZ2 = TZ1+TZS
        TIS = TI
        QBC = QBC5
        GOTO 1553
1520    MGO = MGW
        MUGA = MUGS
        MFA = MFS
        N = N+1
        MU = MUD
        JJ = JJ+1
        TIS = TI
        TZ1 = TZ2+TZ6
        QBC = QBC4
        GOTO 1551
1540    MGO = MGW
        MUGA = MUGW
        MFA = MFS
        N = N+1
        JJ = 1
        MU = MUD
        TIS = TI
        QBC = QBC3
        TZ2 = TZ1+TZS
        GOTO 1550

1204    MGO = MGW
        MF = MF2
        MUGA = MUG2
        N = N+1
        JJ = 1
        MFA = MF
        MU = MUD
        TIS = TI
        TZ1 = TZ2+TZ6
        QBC = QBC2
        GOTO 1550
1210    MU = MUD
        TAUP = TP+MUGA*.134*RHOW/MUD-TPI
        TPIW = 168.0
1550    Write(9,8000) JJ
8000    format(1x, ' YEAR ',I3)
        Write(9,6000)

```

```

6000  format(1x, '                                STANDBY OR WATER WITHDRAWAL ')
      GOTO 1555
1551  Write(9,8000) JJ
      Write(9,6001)
6001  format(1x, '                                SUMMER WATER WITHDRAWAL ')
      GOTO 1555
1553  Write(9,8000) JJ
      Write(9,6002)
6002  format(1x, '                                WINTER WATER WITHDRAWAL ')
1555  Write(9,*)
1580  Write(9,4010) MFA
4010  format(1x, 'BOILER WATER FLOW RATE lbm/hr                                = ',F9.2
)
      Write(9,4011) TWB
4011  format(1x, 'BOILER WATER TEMPERATURE DEG F                                = ',F9.2
)
1610  Write(9,4020) MUGA
4020  format(1x, 'WATER WITHDRAWAL GAL/DAY                                = ',F9.2
)
      Write(9,4021) MUD/(8.04*RHOW)
4021  format(1x, 'WITHDRAWAL FLOW RATE GAL/MIN                                = ',F9.2
)
1640  Write(9,4030) HS
4030  format(1x, 'CONVECTIVE COEFF AFTER R=30 FT BTU/HR-FT2-F                = ',F9.2
)
1672  Write(9,5050) TI
5050  FORMAT(1X, 'START WITHDRAWAL AT HOUR                                = ',F9.2
)
      Write(9,*)
      GOTO 400
1760  Write(9,*)
1790  Write(9,4050) E
4050  format(1x, '      TOTAL ENERGY INPUT BTU                                = ',E15.6)
1820  Write(9,4060) E / 140000
4060  format(1x, '      TOTAL ENERGY INPUT GAL FUEL                        = ',F15.2)
1821  Write(9,4070) QIT
4070  format(1x, '      TOTAL ENERGY LOSS AIR TO ICE BTU                    = ',E15.6)
1850  END

```

# DRAFT

## APPENDIX C: Energy usage for harvesting and transporting snow.

### C.1 Harvesting snow

The amount of energy associated with harvesting snow from the field and transporting it to the melt tank is as follows. Equipment logs for March 2010 (provided from Jay Burnside in email correspondence on 24 June 2010) show that the number of hours the CAT 933 front loader was operated to harvest snow during one week was 12 hrs to deliver 10 buckets of snow, and during a following week it took 10 hours to deliver 12 buckets of snow. Thus, on average it is about 1 hour of CAT 933 operation per bucket load of snow. This is about twice the previous estimates of  $\frac{1}{2}$  hour per bucket load (personal communication with Glenn Helkenn, equipment operator a Summit 24 June 2010).

Also from equipment logs, we obtained a record of how many buckets of snow were delivered each day for the period of 10 May – 23 June 2010. The total number over that period was 171 bucket loads. We also have the water usage during that same time period (email correspondence from Sandy Starkweather 26 Oct 2009) averaged over 3 years (2007-09) which is 15326 gallons. This gives an average of 93 gallons per bucket load. This is consistent with the bucket capacity and snow density. The bucket capacity for the CAT 933 loader is 1.26 cu. yds. or 252 gallons. The specific gravity of the surface snow at Summit is about 0.34 (see Appendix B). Thus a bucket of snow should contain about  $252 \text{ gallons} \times 0.34 = 86$  gallons of water once melted. For this estimate we use 90 gallons of water obtained per bucket load of snow.

From the above, the loader delivers 90 gallons of water per hour. The fuel usage of the CAT 933 (from equipment records provided by Lucas Nordby, station mechanic on 28 June 2010) is about 0.72 gallons of Diesel per hour. Thus, about 125 gallons of water are transported for one gallon of Diesel fuel used. The lower heating value of Diesel fuel is about 126 BTU/gallon (Heywood 1988). Thus, about 1 BTU of energy is needed to harvest a gallon of water and deliver it to the snow melt tank.

### C.2. Water delivery

The water is transported using an Argo vehicle. It takes 45 minutes round trip for the Argo to shuttle 220 gallons of water to the Big House. Per the manufacturers specifications the Argo consumes approximately 0.9 gallons of gasoline per hour. This equates to 245 gallons of water transported per gallon of fuel. The lower heating value of gasoline is about 118 BTU/gallon (Heywood 1988). Thus about 0.5 BTU of energy is required to transport a gallon of water from the shop to the Big House.

### C.3 References

Heywood, J. B. (1988) *Internal Combustion Engine Fundamentals*. McGraw-Hill, New York, NY.